An Atmospheric Mechanism for Generation of Crustal Magnetism on Mars

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In this work, an atmospheric mechanism for the generation of crustal magnetism on Mars is proposed. Here, and alternative to what the standard *ancient dynamo hypothesis* asserts -as per which, the scattered pockets of crustal magnetism on Mars are the remnants of an ancient epoch during which a young Mars might have had a hypothetical sizeable magnetic field- crustal magnetism is generated by the interaction of electrically active dust storms magnetising their own dust with the formation of heavy clusters , which snow out of the atmosphere and are deposited in the Martian soil. Using some idealisations, an upper limit for the mass loading of the magnetised dust that could be generated per lightning strike for a given dust storm was estimated. The atmospheric theory for the cause of the crustal magnetism of Mars offers a phenomenological explanation for several complexities and patterns observed among the intriguing east-west lineation trending without the requirement of additional hypotheses, which seem to become necessary if the ancient dynamo theory is maintained. Furthermore, the atmospheric mechanism for the generation of the crustal magnetism on Mars -which is currently active- holds irrespective of the validity of an ancient dynamo on Mars; however, whether the mechanism was partially or entirely responsible for the largest magnetic anomalies observed on Mars still remains an open question. Further, if this atmospheric mechanism was involved, and if a simple deposition of magnetised clusters driven by seasonal global dust storms over the years cannot account for the largest anomalies, it can be concluded that it was necessary for a large impact to have occurred owing to which vast amounts of dust were ejected into the atmosphere. Although the hypothesis of the occurrence of a large impact is also shared by the dynamo theory, there is a fundamental difference between these two hypotheses: in the atmospheric theory, the large impact does not eliminate any pre-existent remnant magnetism, as in the case of the dynamo theory, but the impact itself creates the magnetism.

Keywords. *Mars; Dust storms, Crustal magnetic field, Dynamo theory*

I. INTRODUCTION

The objective of this work was to analyse a possible mechanism for the generation of a crustal magnetic field on Mars driven by the atmosphere and more precisely by the self-interaction of electrified dust storms magnetising their own dust, with the formation of heavy magnetic clusters that then snow out of the atmosphere, are transported by the winds, and are finally deposited in the Martian soil. This atmospheric mechanism which is currently active, offers an alternative explanation to the ancient dynamo hypothesis, which states that the scattered pockets of crustal magnetism on Mars could be the remnants of an ancient epoch during which the young Mars might have had a hypothetical sizeable magnetic field driven by the circulating motion of molten material within its core. Several spatial features observed in the crustal magnetism of Mars can be explained by the aforementioned atmospheric mechanism without the need for additional hypotheses, which seem to become necessary if the ancient dynamo theory is maintained. For the interested reader, the complete and condensed bibliographic material on Mars' crustal magnetism can be found in [1]. Finally, although the atmospheric mechanism for the production of crustal magnetism holds irrespective of the validity of the existence of an ancient dynamo on Mars, whether the mechanism was partially or entirely responsible for the larger magnetic anomalies observed on Mars and even precludes the need for an ancient dynamo mechanism remains an open question for the planetary community. However, owing to some intriguing observations regarding the anomalies, the contribution of this mechanism cannot be ruled out without sufficient careful analysis.

Only two conditions are required to be simultaneously fulfilled to make the proposed atmospheric mechanism possible for the continuous generation of a crustal magnetic field on Mars: **(1)** there must be electrical activity in the dust storms, and **(2)** the Martian dust must be magnetic. Both these conditions seem to have been extensively demonstrated in recent years by theoretical and detailed laboratory studies as well as numerical simulations and data obtained from the recent Mars mission.

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II. STATEMENT OF THEORY

To begin with, although the proposed atmospheric mechanism for the magnetisation of the material driven by lightning strikes on Mars seems to be, a priori, an ad hoc mechanism for the red planet, it is not. Moreover, the magnetisation of the material surrounding lightning strikes on Earth was identified long ago in 1897 by the German scientist Pockels, who discovered that basalt rocks in the vicinity of lightning strikes were highly magnetised, and from the magnitude of this magnetisation, Pockels was able to provide the first accurate estimation of the currents involved in a lightning strike [2].
The mechanism proposed for the Mars magnetic field is essentially the same, but with a fundamental difference: here it is assumed to occur not in the surface of the planet and with a very soft magnetic material as is basalt on Earth but in the atmosphere with the ubiquitous presence of suspended dust which actually is strongly magnetic.

Only two fundamental conditions must be simultaneously satisfied inside the dust storms for the mechanism to occur: **(1)** there must be electrical activity inside the storm; and **(2)** the dust must be magnetic, in the sense that it can be magnetised by external magnetic fields. Both these conditions seem to have been extensively demonstrated in recent years in theoretical and detailed laboratory studies as well as numerical simulations and direct data obtained from the recent Mars mission, as is briefly discussed below.

A. Electric dust storms on Mars

Since the 1970s, the possibility of important electrical activity on Mars has been speculated. Furthermore, with the twin Viking landers (1976), it was suggested that the activity of the Martian soil detected in the release and gas exchange experiments could be due to electrically active dust storms -similar to the thunderstorms that occur on Earth- and that these storms might be a source of the observed reactive chemistry. Nevertheless, the dust storm hypothesis remained dormant for almost 30 years, until the recently conducted detailed laboratory studies, numerical simulations , and desert field tests by the University of California at the Berkeley Space Science Laboratory and the University of Michigan in Ann Arborm [3], [4], which provide ample evidence that the conditions of the Martian atmosphere should produce strong electrical fields during dust storms. The calculations show that these dust-storm electric fields on Mars can approach the ambient breakdown field strength of $\sim$ 25kV/m. The large electrostatic fields predicted to occur in Martian dust storms can energise electrons in the low-pressure Martian atmosphere to energy values exceeding the electron dissociative attachment energy of both CO_2 and H_2O and then provide a key ingredient for the generation of oxidants [4].

B. Magnetic properties of the Martian dust

Since the Viking missions to Mars (1976) and the Mars Pathfinder mission (1997), it has been established that the Martian soil and airborne dust is magnetic, i.e., the material is attracted to small permanent magnets[5]. However, only with the Mars Exploration Rovers was it possible to identify the ferrimagnetic mineral responsible for the magnetism of the Martian dust. The particles suspended in the Martian atmosphere appear to be composites consisting mainly of silicate phases covered with iron oxides or cemented by iron oxides (and/or sulphates) and containing a few percent of a strongly magnetic (ferrimagnetic) mineral, which may be maghemite (γ-Fe_2O_3). The saturation magnetisation of pure maghemite is 70 A m^2 kg^{-1}, and the saturation magnetisation of the dust has been estimated to be within 1 A m^2(kg soil)$^{-1}<$ $M_s <$4 A m^2(kg soil)$^{-1}$ [6]. It has also been suggested that all the particles suspended in the atmosphere have a similar composition, which implies that the particles are all somewhat magnetic [5],[7], [8].

C. Atmospheric magnetisation

With the two conditions to be satisfied, i.e., electrical activity inside the dust storm and the magnetic properties of their own dust, we can proceed to determine what would happen when a lightning strike occurs.
Let us assume that at a given time inside an electrically active dust storm , a lightning strike occurs with a certain current I. Then, the magnetic material embedded in the micrometre-sized airborne dust surrounding the lightning is instantaneously magnetised. As a first approximation, the lightning strike may be represented as a long straight current-carrying wire, and thus, the magnetic field strength (magnitude) may be easily calculated using Ampere's law as follows.

$$H(r) = \frac{1}{2\pi}\frac{I}{r} \tag{1}$$

where r is the shortest distance to the lightning strike. Moreover, by assuming that the magnetic particles are non-interacting with each other, an upper limit for the instantaneous magnetisation induced by the magnetic field may be estimated according with the Langevin law [9].

$$\frac{M}{M_s} \approx \coth(\alpha) - \frac{1}{\alpha} = L(\alpha) \tag{2}$$

where M_s is the saturation magnetisation of the dust particle, and $L(\alpha)$ denotes the Langevin function with

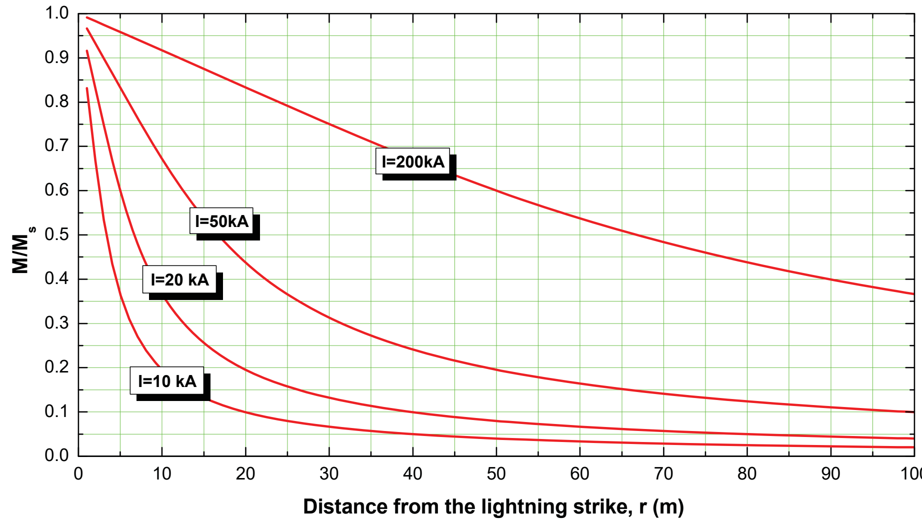

FIG. 1. Calculated magnetisation curves for monodisperse spherical particles of dust as a function of the distance of the lightning strike. .

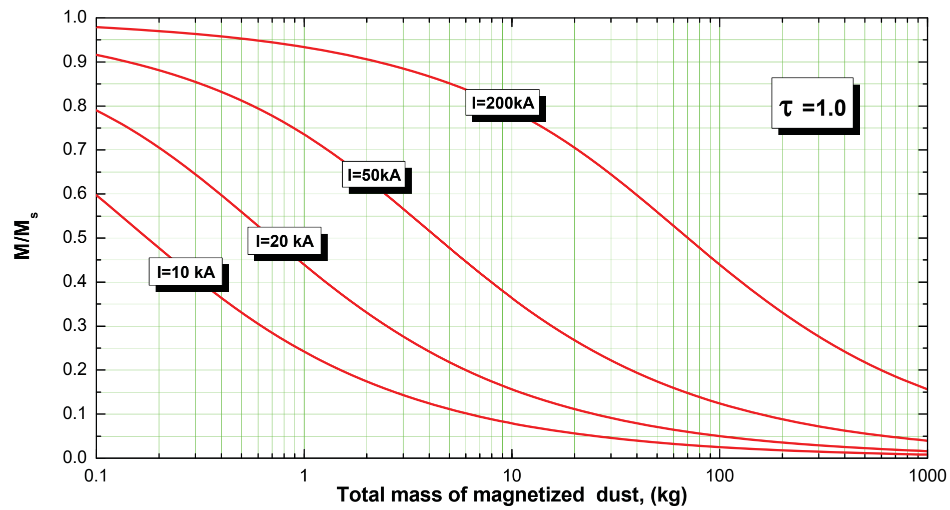

FIG. 2. Mass of magnetised dust with magnetisation $\leq \frac{M}{M_s}$ per lightning strike for dust storm $\tau = 1.0$

$$\alpha = \frac{6\mu_o M_d d^3 H}{\kappa T} \tag{3}$$

where M_d is the saturation moment of the bulk magnetic solid (maghemite-γ-Fe_2O_3 in our case); d is the diameter of the magnetic particle embedded in the micrometre -sized airborne dust; κ is the Boltzmann constant; and T is the absolute temperature. In Eq.(3), the magnetic field is given by Eq.(1), and thus, Eq. (3) may be rewritten as

$$\alpha(r) = \frac{12\mu_o M_d d^3}{\kappa T}\frac{I}{r} \tag{4}$$

which is a function of the distance r.

III. RESULTS AND DISCUSSION

In order to obtain some idea of the shape of the curves predicted by Eq.(2), we assume some values of the parameters: $\mu_o = 4\pi \times 10^{-7}$ Hm; $\kappa = 1.38 \times 10^{-23}$ m^2 kg s^{-2} K^{-1} at an average temperature $T = 210$ K. The saturation magnetisation of the bulk solid $M_d \sim 10 \times 10^5$ A m^{-1} for maghemite; $d \sim 10$ nm. The resulting curves are shown in Fig. 1 for the lightning strikes in the range 10 kA to 200 kA, as has been reported on Earth.

Finally, in an attempt to set an order of magnitude in the production of magnetised dipoles obtained from the storm, an approximate estimation may be obtained by considering the mass loading (g cm^{-2}) of dust. Many semi-empirical formulations for the mass loading of dust storms as function of the optical depth are available in

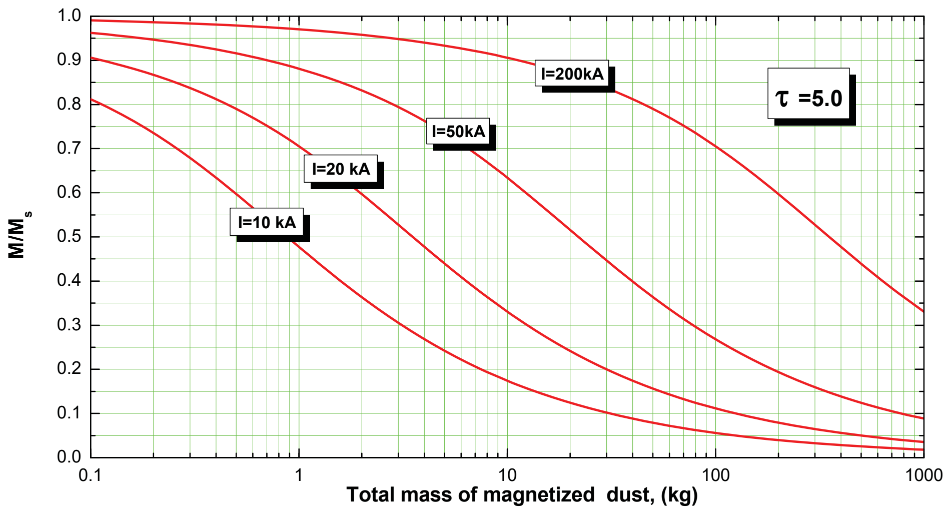

FIG. 3. Mass of magnetised dust with magnetisation $\leq \frac{M}{M_s}$ per lightning strike for a dust storm $\tau = 5.0$

the literature [10], [11]), [12]; however, in view of the uncertainty of the calculation, the simplest expression presented by Pollack for dust with a 2.5μm mean particle radius seems preferable [13].

$$m = 5.0 \times 10^{-4}\tau \tag{5}$$

Using this expression, the upper limits of the total mass of the magnetised dust with magnetisation $\leq \frac{M}{M_s}$ per lightning strike for dust storms with optical depths $\tau = 1.0$ and $\tau = 5.0$ are obtained, as shown in Figs. 2 and 3 , respectively.

It should be stressed that the reported upper limits for the production of magnetised dust per lightning strike inside the dust storms were calculated based on idealisations and are, therefore, not intended to typify estimates. The magnetisation of the dust inside the storms by electrical discharges could be a very complex and difficult mechanism to accurately predict. Substantial uncertainties are present at every step of the analysis, and it should be borne in mind that the atmospheric theory for the generation of crustal magnetism on Mars has more to do with meteorology than classic geomagnetism. Thus, obtaining accurate predictions is as difficult as obtaining accurate weather forecasts on Earth. Moreover, till date, the theory of the formation of thunderstorms is not well understood and is almost phenomenological.

The atmospheric mechanism for the generation of crustal magnetism discussed in this paper provides an easy explanation for several spatial features observed in the crustal magnetism on Mars without the need for recourse to additional hypotheses, which seem to become necessary if the ancient dynamo theory is maintained. For example, the entire Mars spectrum seems to be well described by a random distribution of dipoles [14], [15], which seems to be consistent with a model of atmospheric deposition of magnetised clusters falling from the sky. However, perhaps the most intriguing feature is the organised east-west-trending lineations (see Fig. 4), which remains a mystery till date. In order to justify such a trending within the framework of the ancient dynamo theory, controversial additional supporting models such as the crustal spreading model or even the reversing dynamo model [1] are required, which raise more questions than they answer. However, the reason for the intriguing east–west trending is phenomenologically explained in a simple manner by the atmospheric theory, as shown in Fig. 5, which is self-explanatory. This figure shows the general atmospheric circulations model for Mars while considering a single-cell model (Fig. 5a) and three-cell circulation model (Fig. 5b) that takes into consideration the Coriolis forces. After the magnetisation and formation of clusters, the heaviest clusters would snow out of the atmosphere and deposit locally in the Martian soil; however, in the case of small- and medium-sized clusters, the planetary Hadley circulation of Mars is capable of transporting them quickly to very great heights in its ascending branch, as well as over large latitudinal distances from the southern hemisphere well into the northern hemisphere and with a certain tendency to accumulate in the high northern latitudes while driven by the same Hadley cell; this is a feature that has been mapped on Mars [16]. However, the global atmospheric drifting acts as a type of conveyor belt that has a marked trend of transporting and depositing the magnetic clusters in the large intertropical convergence zones (see Fig. 5a), which translate in the apparent east-west-trending observed in the crustal magnetism. This phenomenon of atmospheric transport and deposition of the magnetised clusters would be much more enhanced if the Coriolis forces are taken into consideration while using a three-cell circulation model, as depicted in Fig. 5b. On referring to this three-cell circulation model, it is easy to obtain the impression that this model or a similar model of atmospheric circulation could explain for the three large east-west lineations observed between Terra Cimmeria and Terra Sirenum (see Fig. 4) -a feature that is difficult to explain within the previously mentioned ancient dynamo theory.

A. Largest magnetic anomalies of Mars

Although the atmospheric mechanism for the generation of crustal magnetism on Mars, which is currently active, holds irrespective of the validity of an ancient dynamo on Mars, whether the mechanism was partially or entirely responsible for the largest magnetic anomalies observed on Mars and specially at Terra Cimmeria and Terra Sirenum remains an open question for the planetary community. Unfortunately, at present, our knowledge on the production of magnetised clusters driven by electrically active dust storms can only be theoretically defined in a manner similar to the production of hydrogen peroxide owing to similar electrical activity. Both the intensity and frequency of the lightning strikes inside the dust storms are unknown, and therefore, the corresponding estimations are purely conjectural; nevertheless, they can provide at least an order of the magnitude. For example, a simple deposition of magnetised clusters over the years driven by seasonal global dust storms can be estimated using the mass loading of dust given by Eq.(5). According to this expression, a column with an optimistic optical depth $\tau = 5$ contains approximately 2.5×10^{-3} g cm^{-2} of dust, which is sufficient for forming a layer ~ 10 μm, while assuming that only a fraction, say 1%, is magnetised by the electrical activity and snowed out of the atmosphere as magnetised clusters. It will translate into a layer ~ 0.1 μm of magnetised dipoles in the Martian soil per year -assuming the occurrence of only one such large dust storm per year. Even if a very optimistic assumption is considered, as per which the convective currents are able to concentrate this amount of magnetised clusters into longitudinal halos with the east-west-trending lineations observed, the order of concentration will be ten-fold at best, i.e., approximately ~ 1 μm per year or ~ 1 meter per myr. Nevertheless, this model of simple continuous atmospheric magnetisation and deposition of clusters in the Martian soil cannot account for the large spot observed between Terra Cimmeria and Terra Sirenum unless it is considered that there exists a persistent low-pressure region at this part of the Martian atmosphere, which produces cyclonic storms; however, the latest careful observations have not revealed such conditions in the region, and its existence is thus highly doubtful. Therefore, if a simple deposition of magnetised clusters over the years driven by seasonal global dust storms cannot account for the large magnetic anomalies, but if the atmospheric mechanism was actually involved, it can be concluded that it was necessary for a large impact to have occurred that caused vast amounts of dust to be ejected into the atmosphere. Furthermore, although the dynamo hypothesis also considers such a large impact, there is an important difference between these hypotheses: in the atmospheric theory, the large impact does not eliminate any pre-existent remnant magnetism, as is the case in the dynamo theory, but the impact is actually the cause of the creation of the magnetism.

IV. SUMMARY OF RESULTS AND CONCLUSIONS

In this work, an atmospheric mechanism for the generation of crustal magnetism on Mars driven by the electrical activity of dust storms and magnetic properties of the dust was discussed. The crustal magnetism is continuously generated by the interaction of electrically active dust storms magnetising their own dust with the formation of heavy clusters that snow out of the atmosphere and deposit in the Martian soil; this hypothesis provides an alternative explanation for the crustal magnetism of Mars to the ancient dynamo hypothesis. An upper limit for the mass loading of the magnetised dust that could be generated per lightning strike in a dust storm with a given dust opacity was estimated.

The atmospheric theory for the production of the crustal magnetism of Mars offers a phenomenological explanation for several complexities and patterns observed among the intriguing east–west trending without the need for additional hypotheses, which seems to become necessary if the previous dynamo theory is maintained.

Finally, although the atmospheric mechanism for the generation of crustal magnetism on Mars, which is currently active, holds irrespective of the validity of an ancient dynamo on Mars, whether the mechanism was partially or entirely responsible for the largest magnetic anomalies observed on Mars remains an open question. However, if it was involved, and if a simple deposition of magnetised clusters over the years driven by seasonal global dust storms cannot account for the largest anomalies, it can be concluded that it was necessary for a large impact to have occurred owing to which vast amounts of dust were ejected into the atmosphere. Although the idea of a large impact is also shared by the ancient dynamo theory, there is a fundamental difference between these theories: in the atmospheric theory, the large impact does not eliminate any pre-existent remnant magnetism, as in the case of the dynamo theory, but actually causes the creation of the magnetism.

- **Testing the atmospheric theory**

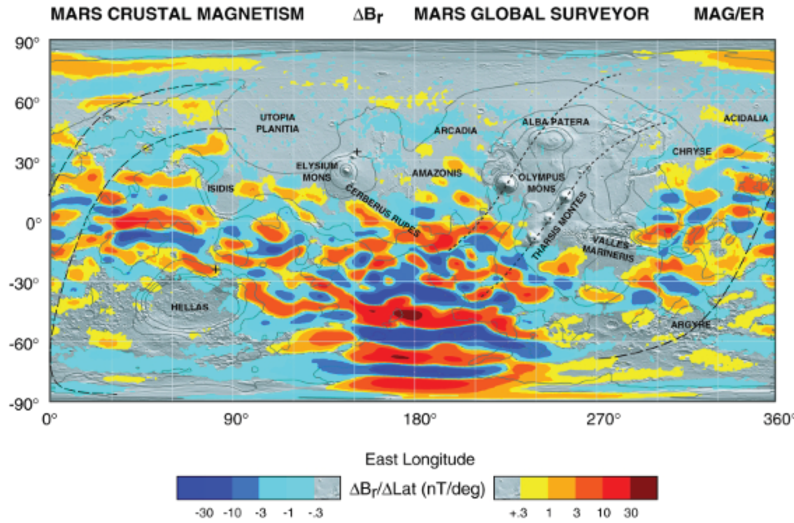

FIG. 4. Magnetic map of Mars. Credit: NASA.

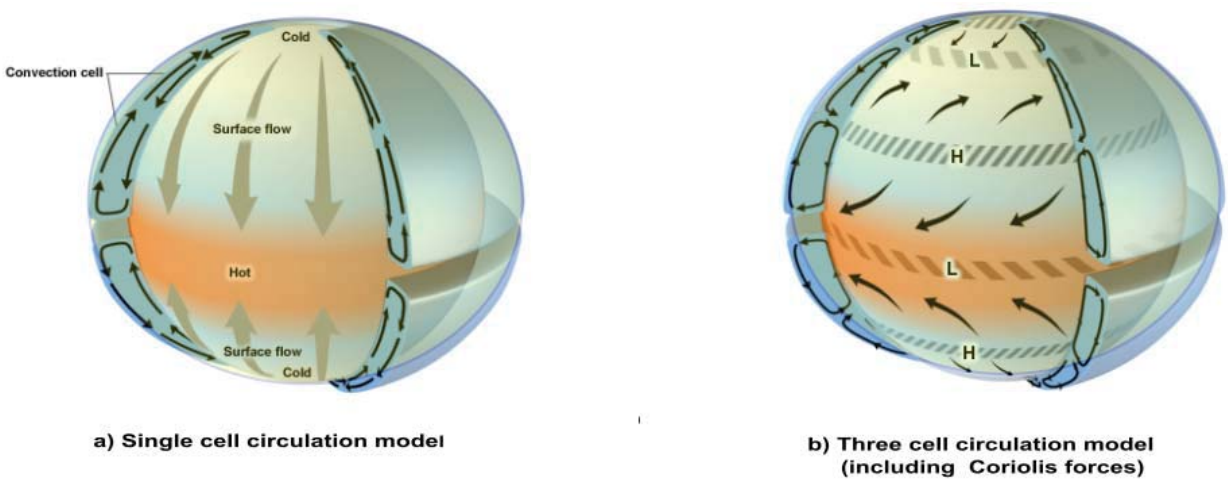

FIG. 5. Schematic of the general Hadley cell circulation on Mars. **a)** Single cell circulation. **b)** Three-cell circulation model including Coriolis forces. Credit: NASA.

The atmospheric theory for the production of crustal magnetism on Mars could be easily tested by carefully measuring the local concentrations of hydrogen peroxide in the magnetic anomalies. Moreover, according to the atmospheric model for the generation of crustal magnetism on Mars, the magnetised clusters are generated by the electrical activity of dust storms, but this is precisely the same mechanism that is claimed to be responsible for the mismatch in the excess concentration of hydrogen peroxide H_2O_2 detected on Mars, as discussed in the preceding section [3],[4].

Therefore, within the atmospheric hypothesis, it is expected that the magnetic anomalies on Mars should also be anomalies of hydrogen peroxide. This simple test is of crucial importance because, if high concentrations of hydrogen peroxide are associated with the magnetic anomalies, this would be a very powerful argument in favour of the atmospheric theory because there is no other mechanism known thus far that can connect the magnetic anomalies with the concentrations of H_2O_2 and also definitively prove the existence of electrical activity in dust storms and the generation of hydrogen peroxide inside them.

However, if high concentrations of H_2O_2 are not detected in the magnetic anomalies, it would not be a definitive proof against the atmospheric theory because although both magnetised clusters and H_2O_2 are generated inside the storm, they can be transported differently by convective currents.

NOMENCLATURE:

d = diameter of magnetic crystallites embedded in the dust particle
H = magnetic field
I = intensity of current
r = radial distance
L = Langevin function
m = atmospheric mass loading of dust
M = magnetiszation
T = temperature

Greek symbols
α = parameter given by Eq.(3)
κ = Boltzmann constant
μ_o = permeability of free space
τ = optical depth dust storm

subscripts
s = saturation

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